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Supernovae evidence for foundational change to cosmological models

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ABSTRACT

We present a new, cosmologically model-independent, statistical analysis of the Pantheon+ Type Ia Supernovae spectroscopic data set, improving a standard methodology adopted by Lane et al. We use the Tripp equation for supernova standardization alone, thereby avoiding any potential correlation in the stretch and colour distributions. We compare the standard homogeneous cosmological model, i.e. spatially flat Λ cold dark matter (ΛCDM), and the timescape cosmology which invokes backreaction of inhomogeneities. Timescape, while statistically homogeneous and isotropic, departs from average Friedmann–Lemaître–Robertson–Walker evolution, and replaces dark energy by kinetic gravitational energy and its gradients, in explaining independent cosmological observations. When considering the entire Pantheon+ sample, we find very strong evidence ($\ln B > 5$) in favour of timescape over ΛCDM. Furthermore, even restricting the sample to redshifts beyond any conventional scale of statistical homogeneity, $z > 0.075$, timescape is preferred over ΛCDM with $\ln B > 1$. These results provide evidence for a need to revisit the foundations of theoretical and observational cosmology.

Key words: gravitation – supernovae: general – cosmological parameters – dark energy – cosmology: theory.

1 INTRODUCTION

The Λ cold dark matter (ΛCDM) model, which has served as the standard cosmological model for quarter of a century, is facing serious challenges in light of recent results (Abbott et al. 2024; Adame et al. 2024) and may need to be reconsidered at a fundamental level (Di Valentino et al. 2021; Peebles 2022; Aluri et al. 2023). In this Letter, we present definite statistical evidence that the timescape cosmological model (Wiltshire 2007a, b, 2009) outperforms ΛCDM in matching Type Ia Supernovae (SNe Ia) observations. It may provide not only a viable alternative to the standard cosmological model, but ultimately a preferred one. This result potentially has far-reaching consequences not only for cosmology, but also for other key aspects of astrophysical modelling from late epochs to the early universe.

We perform an empirical cosmologically independent analysis within which both the ΛCDM and timescape cosmologies may be embedded, and thus compared via Bayesian statistics. The timescape model is a particular implementation of Buchert's scalar averaging scheme which incorporates backreaction of inhomogeneities (Buchert 2000, 2001; Wiltshire 2014; Buchert, Mourier & Roy 2020). Instead of a matter density parameter relative to average Friedmann–Lemaître–Robertson–Walker model (as in ΛCDM), timescape is characterized by the *void fraction*, $f_{\rm v}$, which represents the fractional volume of the expanding regions of the universe made up by voids.

A key ingredient of the timescape model is a particular integrability relation for the Buchert equations: the *uniform quasi-local Hubble expansion* condition. Physically, it is motivated by an extension of Einstein's Strong Equivalence Principle to cosmological averages at small scales ($\sim 4-15$ Mpc) where perturbations to average isotropic expansion and average isotropic motion cannot be observationally distinguished (Wiltshire 2008).

In standard cosmology, differences from average FLRW expansion are assumed to be mostly attributed to local Lorentz boosts – i.e. peculiar velocities – of source and observer, with gravitational potentials contributing fractional variations of $\sim 10^{-5}$ of average expansion at galaxy and galaxy cluster scales. In timescape, the same fractional variation can be up to $\sim 10^{-3}$ and the equivalence of different choices of background, via the Cosmological Equivalence Principle, means that notions of average isotropic expansion persist well into the non-linear regime of structure formation. The signature of the emergent kinetic spatial curvature of voids has now been identified in cosmological simulations using full numerical general relativity without Λ (Williams et al. 2024).

Both the standard cosmology and the timescape model agree empirically on a Statistical Homogeneity Scale (SHS), typically given as $z_{\rm CMB} \sim 0.033$ by the two-point galaxy correlation function (Hogg et al. 2005; Scrimgeour et al. 2012; Dam, Heinesen & Wiltshire 2017). Timescape offers its most important tests and predictions below the SHS, at scales where the filaments, sheets and voids of the cosmic web are still expanding but in the non-linear regime.

To conduct our analysis, we use the largest spectroscopically confirmed SNe Ia data set, Pantheon+ (Scolnic et al. 2022). SNe Ia have

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been a pillar for informing the distance ladder used for cosmological model comparison, and have a rich history in revolutionising the field (Riess et al. 1998; Perlmutter et al. 1999). More modern methods for standardizing SNe Ia light curves use the SALT2 fitting algorithm (Guy et al. 2007; Taylor et al. 2021), as used by Pantheon+, and more recently SALT3 (Kenworthy et al. 2021) used by the Dark Energy Survey 5-year release (DES5yr; Abbott et al. 2024). The SALT fitting algorithms fit the distance moduli, μ, using a modified version of the Tripp formula:

$$\mu = m_{\rm B}^{*} - M_{\rm B} + \alpha x_1 - \beta c, \tag{1}$$

where α and β are considered constant across all redshifts[1], x_1 is the time stretch/decay parameter, c is the colour, and $m_{\rm B}$ and $M_{\rm B}$ are the apparent and absolute magnitude in the rest frame of the B band filter. Rest-frame measurements are identical for theories obeying the Strong Equivalence Principle of general relativity – in particular, in both the FLRW and timescape models. In our analysis, x_1, c, and $m_{\rm B}$ are taken directly from the Pantheon+ data.

The observational distance modulus from equation (1) is then compared with the theoretical distance modulus, given by

$$\mu \equiv 25 + 5\log_{10}\left(\frac{d_{\rm L}}{\rm Mpc}\right), \tag{2}$$

which is determined using the bolometric flux. The luminosity distance, $d_{\rm L}$, can be calculated using the redshift of the supernovae and suitable cosmological model parameters. Typically, these are $\Omega_{\rm M0}$ for the spatially flat ΛCDM model and $f_{\rm v0}$ for the timescape cosmology.[2] Thus, the distance modulus constitutes the pillar of cosmological model comparison via supernovae analysis.

As noted in Lane et al. (2024), we omit peculiar velocity corrections. These are typically made using FLRW geometry assumptions, making it impossible to include them while preserving model-independence, or to perform a fair comparison. However, as distinctions between peculiar motion and expansion are central to the further development of timescape, the inclusion of such corrections will be addressed in future work. We would expect such corrections to have a small impact for low-redshift data cuts and negligible impact for $z_{\rm min}$ taken within a statistically homogeneous regime (Carr et al. 2022). Furthermore, for the same reasons we do not include other cosmological model and metric-dependent bias corrections, such as Malmquist biases. Such corrections are small and cannot drive any substantial changes to the Bayes factors since the trend with redshift is expected to be very similar[3] in both ΛCDM and timescape.

Lane et al. (2024) already presented moderate preference in favour of the timescape model over ΛCDM. A similar result was also obtained by the DES team, with $z_{\rm min} = 0.033$, using the Akaike Information Criterion on the DES5yr supernovae sample (Camilleri et al. 2024). They further noted a change from $\frac{1}{2}\Delta{\rm AIC} = -1.7$ (in favour of timescape) to $\frac{1}{2}\Delta{\rm AIC} = 6.3$ (in favour of spatially flat ΛCDM), when SNe Ia data were combined with Baryonic Acoustic Oscillation (BAO) measurements. However, the BAO analysis of Camilleri et al. (2024) assumes purely geometric adjustments to the standard FLRW pipeline, using a ΛCDM calibration of the BAO drag epoch, which is not the case in timescape. Incorporating detailed BAO analysis into the timescape cosmology requires extraction of the BAO from galaxy clustering statistics, which has already been implemented (Heinesen et al. 2019). However, since the ratio of baryonic matter to non-baryonic dark matter is different from ΛCDM, matter model calibrations in the early universe must also be revisited.

[1]For Pantheon+, Scolnic et al. (2022) adopt values of $\alpha = 0.148$ and $\beta = 3.112$, respectively, for their nominal fit.

[2]See Dam et al. (2017, appendix A) for detailed comparisons of luminosity distance calculations in the timescape and FLRW models.

[3]The principal small difference occurs in the geometric homogeneous Eddington bias (McKay 2016), leading to the potential for future tests.

2 STATISTICAL ANALYSIS

We determine Bayes factors, B, using the standard Jeffrey's scale (Kass & Raftery 1995) for model comparison, whereby $|\ln B| < 1$ indicates no statistical preference, $1 \leq |\ln B| < 3$ moderate preference, while $3 \leq |\ln B| < 5$ and $|\ln B| \geq 5$ represent strong and very strong preference respectively. In this Letter, positive (negative) $\ln B$ values indicate a preference for the timescape (spatially flat ΛCDM) model.

Bayesian statistics have already been implemented on SNe Ia data for cosmological analysis, originally in the SDSS one-year sample (Kessler et al. 2009; March et al. 2011) but later extended to the Joint Light curve Analysis (Betoule et al. 2014) sample (Nielsen, Guffanti & Sarkar 2016; Dam et al. 2017) and more recently in the Pantheon+ (Brout et al. 2022a, b; Scolnic et al. 2022) data set (Lane et al. 2024).

The previous studies implemented a Bayesian hierarchical likelihood construction in the form

$$\begin{aligned}\mathcal{L} &\equiv \prod_{i=1}^{N} \Pr\left[(\hat{m}_{\rm B}^{*}, \hat{x}_1, \hat{c})_i \,\middle|\, H\right] \\ &= \prod_{i=1}^{N} \int \Pr\left[(\hat{m}_{\rm B}^{*}, \hat{x}_1, \hat{c})_i \,\middle|\, (M_{\rm B}, x_1, c)_i, H\right] \\ &\quad \times \Pr\left[(M_{\rm B}, x_1, c)_i \,\middle|\, H\right] {\rm d}M_{\rm B}{\rm d}x_1{\rm d}c,\end{aligned} \tag{3}$$

where the quantities which are denoted with a hat are considered to be observed values, the true values are the quantities not denoted by a hat, and N is the number of supernovae observations. The true data represents the intrinsic parameters utilised explicitly in the Tripp (Tripp 1998) relation.

Nielsen et al. (2016), Dam et al. (2017), and Lane et al. (2024) follow the analysis of March et al. (2011) and adopt global, independent Gaussian distributions for $M_{\rm B}$, x_1, and c to determine the probability density of the true parameters. However, both of these simplifying assumptions are ultimately flawed. Indeed, (i) the true values of x_1 and c are expected to be highly correlated as these are effective parameters obtained by coarse-graining the highly complex processes behind supernovae explosions; (ii) both the distributions of x_1 and c present strong non-Gaussian features that cannot be explained away by systematics or biases in the data. Whilst the former always represented an overly simplifying assumption, the latter was a reasonable assumption when it was first implemented, however, the vast increases in observed SNe Ia have shown the second assumption to be flawed (Hinton et al. 2019).

To overcome the faulty assumptions of the previous analyses, a full non-Gaussian modelling of the joint distribution for x_1 and c would be required. This represents non-trivial changes in the likelihood construction and integration, which will be addressed in future work (in prep.). Therefore, in this Letter, we propose an alternative approach to sidestep the issue. Our new approach builds upon the Bayesian hierarchical likelihood construction method by directly seeding the priors of x_1 and c with the inferred values from the SALT2 fitting algorithm (Guy et al. 2005, 2007; Taylor et al. 2021). Specifically, we define the priors over the true values for each

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supernovae as

$$\Pr\left[(M_{\rm B}, x_1, c)_i \middle| H\right] = \mathcal{N}\left(M_{\rm B}|\bar{M}_{\rm B}, \sigma_{M_{\rm B}}\right)\delta(x_1 - \hat{x}_{1,i})\,\delta(c - \hat{c}_i)\,, \tag{4}$$

where $\mathcal{N}(M_{\rm B}|\bar{M}_{\rm B}, \sigma_{M_{\rm B}})$ is a normal distribution with mean value $\bar{M}_{\rm B}$ and variance $\sigma^2_{M_{\rm B}}$, and δ is the Dirac delta distribution. Thus, the prior distribution in $M_{\rm B}$ is common to all the supernovae data, while the priors in x_1 and c are supernovae specific. Therefore, our new approach sidesteps the problem of modelling the joint distribution, only requiring five parameters (a cosmological parameter, α, β, $M_{\rm B}$, and $\sigma^2_{M_{\rm B}}$), by assuming that the SALT2 parameters represent the 'true' parameters, i.e. the most probable values for both x_1 and c for this version of the SALT model.

Equivalently, given a single-shot inference for any physical quantity, the best guess for its true value is precisely the one inferred through the observational procedure. The assumption of being the most probable value introduces a caveat that it may, however, potentially overlook astrophysical systematics inherent in the SALT2 light-curve procedure.

Our approach here has essential differences from previous methodology (Nielsen et al. 2016; Dam et al. 2017; Lane et al. 2024), and is not merely a change of priors. Earlier work assumed that all supernovae are drawn from ideal independent Gaussian distributions in stretch (x_1) and in colour (c), with mean values and standard deviations derived from the cosmological fit. In contrast, this study does not assume any particular statistical distribution for x_1 and c, nor do we assume these parameters follow the same ideal distribution across the supernova sample. Instead, x_1 and c are treated as fixed, with values provided by the SALT2 fit. Taylor et al. (2021) show through simulations that SALT2 reliably recovers input supernova parameters. To compare this method with the previous one, we use the same data set as Lane et al. (2024).

Therefore, by now following the same procedure as in Lane et al. (2024), we find the likelihood to be

$$\mathcal{L} = (2\pi)^{-3/2}\det\left[D + \Sigma_{\rm d}\right]^{-1/2}\exp\left[-\frac{1}{2}X^{\intercal}(D + \Sigma_{\rm d})^{-1}X\right], \tag{5}$$

where the distributional error matrix (D) is the block-diagonal matrix with each block defined as diag $\left(\sigma^2_{M_{\rm B}}, 0, 0\right)_i$, $\Sigma_{\rm d}$ is the $3N \times 3N$ statistical and systematic covariance matrix given by Lane et al. (2024, section 2), and the residual vector X is defined by

$$\begin{aligned} X := [&\hat{m}^*_{\rm B,1} - \mu_1 - M_{\rm B,1} + \alpha\hat{x}_{1,1} - \beta\hat{c}_1, 0, 0, ..., \\ &\hat{m}^*_{\rm B,N} - \mu_N - M_{\rm B,N} + \alpha\hat{x}_{1,N} - \beta\hat{c}_N, 0, 0]^{\intercal}\,. \end{aligned} \tag{6}$$

Similarly to Dam et al. (2017) and Lane et al. (2024) we utilize a nested Bayesian sampler `PyMultiNest` (Buchner et al. 2014), which interacts with the `MultiNest` (Feroz & Hobson 2008; Feroz, Hobson & Bridges 2009; Feroz et al. 2019) code to compare the spatially flat ΛCDM and timescape models with a tolerance of 10^{-3} and $n_{\rm live} = 800$ for nine parameters. We choose the same priors as Lane et al. (2024, table B2 & section 3) summarized in Table 1.

Finally, in our analysis we reconstruct the $z_{\rm CMB}$ by applying a boost (Fixsen et al. 1996) to the Pantheon + heliocentric redshifts, excluding peculiar velocity corrections. We then remove all supernovae with $z_{\rm CMB} \leq z_{\rm min}$ for varying redshift cuts $z_{\rm min}$ and fit the cosmological model to the remaining supernova events. This allows us to examine how the Bayes factor, cosmological parameters, and Tripp parameters vary across different redshift regimes.

Table 1. Bayesian and frequentist priors on parameters used in the analysis. All priors are uniform on the respective intervals and, importantly, relatively broad for both models to ensure fair comparison.

Parameter	Priors
$f_{\rm v0}$	[0.500,0.799] (2σ bound)
$\Omega_{\rm M0}$	[0.143,0.487] (2σ bound)
α	[0,1]
β	[0,7]
x_1	[−20,20]
c	[−20,20]
$M_{\rm B}$	[−20.3,18.3]
$\sigma^2_{M_{\rm B}}$	$\log_{10}(\sigma)$ [−10,4]

3 RESULTS

Results for the Bayes factor, cosmological and light-curve parameters are shown in Fig. 1.

The Bayesian comparisons are best understood by splitting the minimum redshift cutoff used into three regimes: (i) for $0 < z_{\rm min} < 0.023$ we find very strong to strong evidence on the Jeffrey's scale (Kass & Raftery 1995) in favour of timescape over ΛCDM; (ii) for $0.023 \leq z_{\rm min} < 0.054$ we enter the *calibration regime*,[4] finding moderate to no significant preference for timescape; (iii) for $z_{\rm min} \geq 0.075$, beyond any measure of a SHS[5], we find exclusively moderate preference for the timescape cosmology. Notably, the log-evidence, $\ln Z$, values found here for both models are ∼10–100× greater compared to the previous analysis by Lane et al. (2024).

Since timescape's uniform quasi-local Hubble expansion condition holds down to scales $\sim 4-15$ Mpc, as we decrease $z_{\rm min}$ an increase in the Bayesian evidence favouring timescape is expected if the model accurately captures the average cosmic expansion deep in the non-linear regime of structure formation. Beyond the SHS, ΛCDM of course provides an excellent description of our Universe. However, the evidence in favour of timescape remains small but modest ($\ln B > 1$) at the highest redshift cuts, $z_{\rm min} \geq 0.075$, pointing to the ability of the model to describe the Universe's expansion history on scales greater than the SHS. This moderate evidence ($\ln B > 1$) can be interpreted as resulting from the integrated effects across the redshift range $z_{\rm min} < z < 2.26$, reflecting the 1–3 per cent variations in the expansion history between timescape and ΛCDM.

In comparing two models with different assumptions in the non-linear regime, the redshift distribution of the data becomes particularly important. For example, Lane et al. (2024) found consistent weak preference in favour of timescape using the P+580 subsample in which data from the full sample is truncated at high and low redshifts. While the evidence for the P+1690 sample changes significantly of order $\ln B \sim 1.5-2.5$ in our revised analysis, the P+580 subsample result remains consistent (Fig. 2). The discrepancy between the results of the full data set and the subsample suggest the need for further analysis on how the redshift distribution of supernovae, and the probed redshift range impact evidence for cosmological models. The uncertainty in the Bayes factor, ∼0.014,

[4]This is the regime beyond which average homogeneity and isotropy are assumed to apply to all observations. Hogg et al. (2005); Scrimgeour et al. (2012) take this range as $\gtrsim$ 70–120 h^{-1}Mpc (corresponding to a redshift range of approximately 0.023–0.04).

[5]The Lane et al. (2024) value $z_{\rm min} = 0.075$ is larger than other estimates and thus gives a robust upper bound for the SHS.

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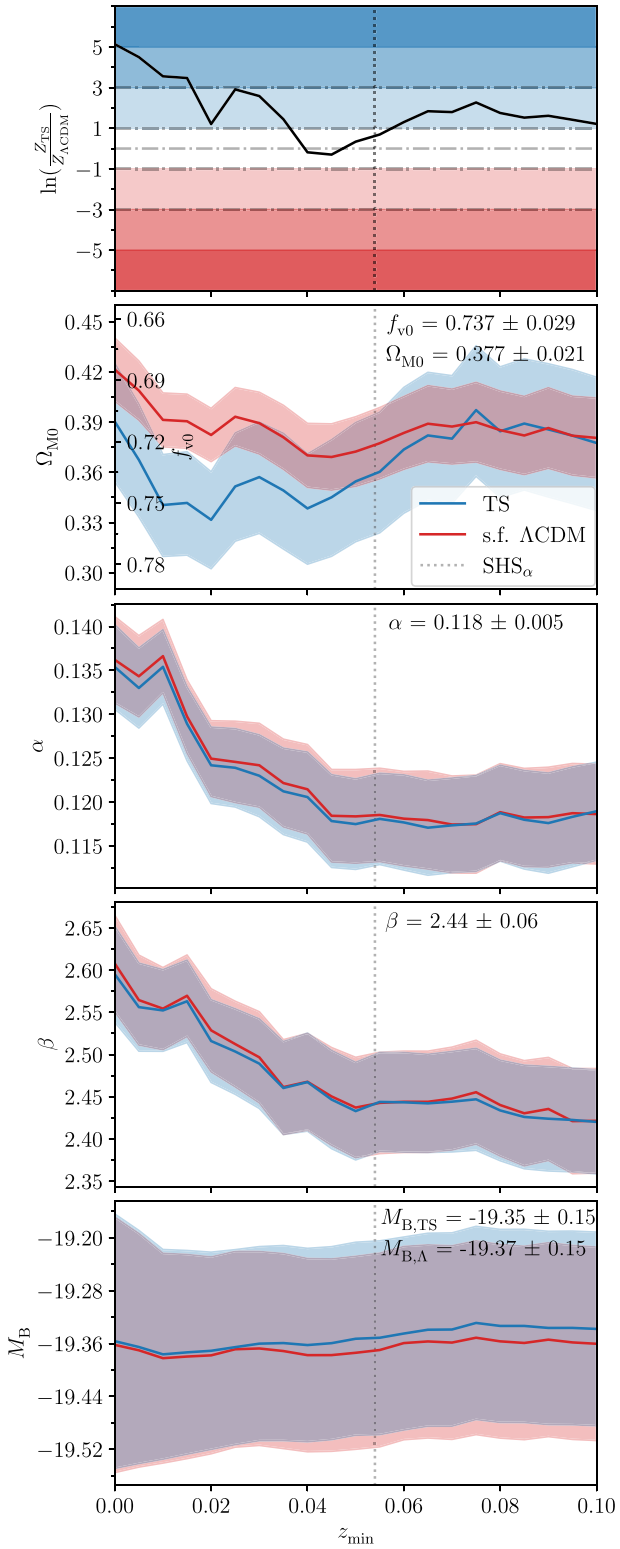

Figure 1. The Bayes factors and Bayesian Maximum Likelihood Estimate (MLE) parameters for the fitting parameters across different redshift cuts, with Bayes factor uncertainties too small to display in the plot. The top plot shows the Bayes factors, where the upper section ($\ln B > 1$) favours timescape, the unshaded section favours neither hypothesis and the lower section ($\ln B < -1$) favours ΛCDM. The following plots show the various MLE parameter estimates, with values beyond $SHS_\alpha = 0.054^{+0.007}_{-0.012}$ indicated by the dashed vertical line.

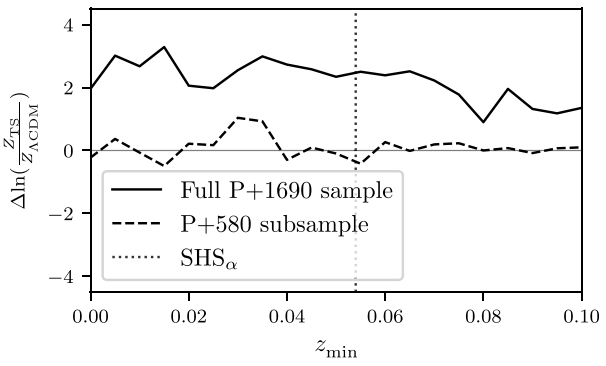

Figure 2. The difference in the Bayes factors for the full P+1690 sample and the P+580 subsample between Lane et al. (2024) and our results. For the subsample, the results from the new analysis presented here align very well with the results by Lane et al. (2024), while for the full sample the new analysis greatly increases the preference in favour of timescape.

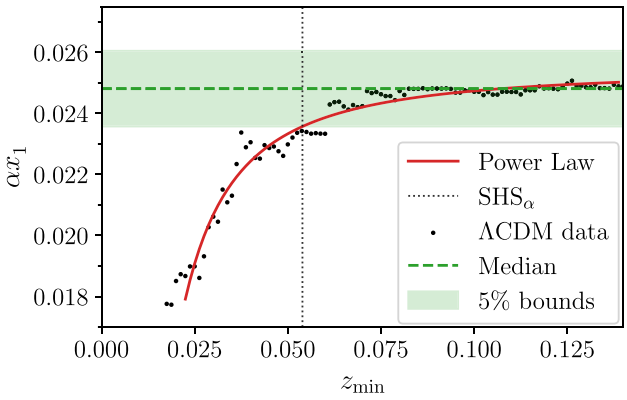

Figure 3. The convergence of the αx_1 light-curve parameter for the spatially flat ΛCDM model across various redshift cuts, where x_1 is the median value from the distribution. A power-law model has been fit to the data, and the shaded band represents within 5 per cent of the median value within the range $0.1 \leq z_{min} < 0.14$ indicating when the model converges. The vertical dotted line represents the SHS_α found at $z_{min} = 0.054^{+0.007}_{-0.012}$. The power-law uncertainty is smaller than the plotted line.

is so small that it does not influence the Jeffrey's scale classifications or the conclusions drawn.

The Bayes factors and Bayesian Maximum Likelihood Estimate (MLE) parameters for different redshift cuts are shown. The top panel shows Bayes factors with blue indicating preference for timescape, red for ΛCDM, and white for neither. The subsequent plots show MLE parameter estimates, with values beyond the scale of the statistical homogeneity (SHS) marked by the dashed vertical line.

Lane et al. (2024) introduced an additional empirical data-driven notion of statistical homogeneity, defining SHS_α from a power law fitted to the αx_1 degenerate parameter. The analogous SHS_β defined from βc does not yield a true convergence for the analysis by Lane et al. (2024), nor for this analysis, due to Malmquist bias not being accounted for. While the SHS_β appears to converge below $z_{min} \approx 0.12$, this is not the case for higher redshift cuts. For the reanalysis presented in Fig. 3 we find $SHS_\alpha = 0.054^{+0.007}_{-0.012}$, which is 1.2σ greater than the maximum value of the SHS gathered from the two-point galaxy correlation function (Hogg et al. 2005; Scrimgeour et al. 2012) and somewhat lower but within 2.3σ of the result Lane et al.

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(2024) determined. The differences with respect to the analysis in Lane et al. (2024) derive from the lifting of the Gaussian assumption of the underlying distributions of x_1 and c.

The Bayesian analysis can be used to find the MLE of the parameters, including the single free cosmological parameter. For $z_{\rm min}$ cuts beyond the SHS$_\alpha$, ($z_{\rm min} \geq 0.055$), for ΛCDM we find $\Omega_{\rm M0} = 0.377 \pm 0.021$, within 1.2σ of the value found from the DES5yr release (Abbott et al. 2024), and just outside of 2σ of Pantheon+ (Brout et al. 2022a).[6]

In the case of timescape, we find a void fraction of, $f_{\rm v0} = 0.737 \pm 0.029$, within 2σ of the Camilleri et al. (2024) DES5yr value. Significantly, our $f_{\rm v0}$ value is also within 2σ of independent values predicted from the Planck CMB power spectrum, $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$ (Duley, Nazer & Wiltshire 2013); and well within 1σ of strong gravitational lensing distance ratios, $f_{\rm v0} = 0.736 \pm 0.099$, (Harvey-Hawes & Wiltshire 2024). We also find the evolution of the Tripp constants, α, β, and $M_{\rm B}$ with varying $z_{\rm min}$ cuts following Dam et al. (2017), Lane et al. (2024). To avoid the underlying degeneracy between H_0 and $M_{\rm B}$, we fix H_0 for both models as a nuisance parameter.[7] Moreover, although the values for the individual parameters differ between the two statistical methods, the Tripp distance modulus, μ, changes on average by only $|\Delta(-M_{\rm B} + \alpha x_1 - \beta c)|_{\Lambda{\rm CDM}} = 0.030 \pm 0.019$ for redshift cuts beyond $z_{\rm min} = 0.054$. This variation is observed when comparing the median values of x_1 and c in the Tripp methodology, to the general Gaussian distribution fit values.

The change in μ between this work and Lane et al. (2024) is thus not statistically significant in this regime. However, it is expected that differences in the prior distribution cause differences in the fitted parameters. This behaviour will be investigated further for supernovae statistics built on skewed, non-Gaussian distributions in future work (in prep.).

In the beams with Bias Correction method (Kessler & Scolnic 2017) a galaxy host correction is introduced with an additional parameter, γ, defined by the mass-step

$$\gamma G_{\rm Host} = \delta_{\rm G.Host} = \begin{cases} \gamma/2 & \text{if } {\rm M}_{\rm Galaxy} \geq 10^{10}{\rm M}_\odot \\ -\gamma/2 & \text{if } {\rm M}_{\rm Galaxy} < 10^{10}{\rm M}_\odot. \end{cases} \quad (7)$$

We examined including this term but found that it does not affect the Bayes factor conclusions, with an average offset of $|\Delta \ln B| = 0.077$ compared to the uncorrected value. Furthermore, the statistical cost of introducing additional free parameters can be assessed by the relative Bayesian Information Criterion (BIC) statistic (Schwarz 1978; Kass & Raftery 1995) BIC $= k \ln N - 2 \ln Z$ for k free parameters, a sample size, N, and likelihood Z. We find that independent of cosmology the model with a mass step is strongly disfavoured relative to the uncorrected Tripp model, with $\Delta{\rm BIC} = -7.90$ at $z_{\rm min} = 0$. Furthermore, there is no significant change in the value of the cosmological parameter, with $\Delta\Omega_{\rm M0} \approx 0.0016$, which is well within the 1σ range of our statistical and systematic uncertainties. Thus our final results are stated without galaxy host corrections.[8]

4 DISCUSSION AND CONCLUSIONS

We performed a new Bayesian statistical analysis on the Pantheon+ supernovae data set, accounting for the non-Gaussian x_1 and c features of the supernovae parameter distributions. The Bayesian evidence yields very strong to strong evidence for the timescape model in the low-redshift regime. This late-universe result could be expected, as the timescape models accounts for non-kinematic differential expansion on scales $z \lesssim 0.03$ where the local inhomogeneous structure of our nearby cosmic web most impacts measurements. On the other hand, for samples strongly weighted by SNe Ia in the calibration regime of the ΛCDM model ($z_{\rm CMB} \approx 0.04$) there is no significant preference either way, the two models being statistically equivalent. With a restriction to higher redshifts, well beyond any scale of statistical homogeneity generally accepted (Lane et al. 2024), Bayesian evidence is driven once again in favour of timescape.

Our new analysis makes fewer assumptions about any particular statistical distribution of the data. Specifically, the likelihood function is constructed directly from the x_1 and c values obtained using the SALT2 algorithm – values employed in most SNe Ia analyses. The empirical SNe Ia data obtained via the cosmology independent SALT2 fit strongly favours the timescape model over ΛCDM.

Any astrophysical or environmental biases would likely impact both cosmological models. Thus the strong preference for timescape would require an extremely subtle combination of such biases for this to be its prime cause. The largest systematic error in the Pantheon+ analysis is the standardization of the heterogeneous mix of low-z sample light curves (Abbott et al. 2024; Lane et al. 2024). Future improvements with the new DES5yr sample (Abbott et al. 2024) will allow for a more homogeneous and careful selection of the low-z sample. However, in this Letter we concentrate on the impact of the new statistical method on cosmological model selection, and therefore we use the same data as Lane et al. (2024).

Since timescape has the same number of free parameters as spatially flat ΛCDM, Bayesian evidence offers the best comparison. To expand our results to include other popular FLRW-type alternative cosmological models, which contain more parameters, e.g. wCDM, we determine the BIC statistic (Schwarz 1978; Kass & Raftery 1995) for fair model comparison. For the full sample, we find that relative to timescape ΛCDM models with FLRW curvature are very strongly disfavoured with $\Delta{\rm BIC} = -13.39$, while wCDM is also very strongly disfavoured with $\Delta{\rm BIC} = -11.70$.

The results presented in this Letter indicate that the timescape cosmology is not only a viable contender to the ΛCDM framework, but may also provide new insights to the astrophysics of modelling SNe Ia. Timescape's non-FLRW average evolution reveals degeneracies between cosmological parameters and empirical SNe Ia model parameters that were already partly uncovered in earlier work (Dam et al. 2017) but which are striking with Pantheon+, as shown by Lane et al. (2024) and the present Letter.

[6]The α and β values reported by Scolnic et al. (2022) and Lane et al. (2024) are derived at various stages of the cosmological fitting pipeline, and are influenced by the specific subsample used (Lane et al. 2024). Any slight differences in cosmological parameters can be attributed to these methodological variations and to the omission of cosmology dependent bias corrections.

[7]The relative contributions of Hubble constant uncertainty and absolute magnitude uncertainty, respectively $\delta_{\rm H_0}$ and $\delta_{\rm M_B}$, propagate according to $\sigma_{\rm M_B} = \left[\delta^2_{\rm M_B} + \left(\frac{5}{H_0 \ln 10}\right)^2 \delta^2_{\rm H_0}\right]^{1/2}$. This makes the two contributions impossible to unravel and explains the larger uncertainty, $\sigma_{\rm M_B}$, relative to uncertainties in other parameters from the fitting (see Fig. 1).

[8]A further reason for not including galaxy-host corrections is the observation that the γ parameter exhibits inconsistent behaviour across different redshift cuts for a simple mass-step function. This inconsistency most likely arises from the heterogeneous subsamples of low-z data, as γ is well constrained in a more statistically homogeneous sample. It is possible, but less likely, that these fluctuations arise from other astrophysical factors explored by the DES5yr team and recent studies (Dixon et al. 2024), but these are beyond the scope of this Letter.

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Regardless of what model cosmology is to be the standard in future, exploring more than one model is important. Indeed, the timescape framework is consistent with new analysis of void statistics in numerical relativity simulations using the full Einstein equations (Williams et al. 2024). These are consistent with an emerging kinetic spatial curvature of voids on small scales. Much remains to be done in calibrating the dark matter fraction, primordial sound speed and the BAO scale. However, new results are likely to provide a robust framework for this (Galoppo & Wiltshire 2024; Galoppo, Re & Wiltshire 2024).

Our results imply profound consequences for cosmology and astrophysics. Indeed, a net preference for the timescape cosmology over the standard FLRW cosmologies may point to a need for revision of the foundations of theoretical cosmology, both ontologically and epistemologically, to better understand inhomogeneities and their backreaction on the average evolution of the Universe.

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DATA AVAILABILITY

A complete set of the codes and details used for our analysis and how to use them can be found at Seifert & Lane (2023), and the covariance and input files are made available at Lane & Seifert (2024).

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